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# **STRUCTURAL AND DYNAMIC COMPLEXITIES OF RISK AND CATASTROPHE SYSTEMS : AN APPROACH BY SYSTEM DYNAMICS MODELLING**

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## **KEYWORDS**

Dynamic modelling, General Systems Theory, Risk analysis.

## **ABSTRACT**

Risk and catastrophe are complex systems. Within the scope of this paper, we focus our attention on structural and dynamic complexities of catastrophes and on the possibility of modelling and simulating its double complexity with a formal and methodological framework: the General Systems Theory and System Dynamics modelling. We then briefly propose a model of urban catastrophe related to a flood. We then propose some ways of research allowing exceeding the limits related to the modelling.

## **INTRODUCTION**

This document aims to apprehend the complexity of the systems of risks and catastrophes in urban environments. The catastrophe is a social and spatial disorganization of the territorial system which is affected by a disturbing event. Based on scientific research on risks and disasters and on our own research, we could identify various forms of complexity. Some of them concern the structural complexity of catastrophes, while others are related to the complexity of spatial and temporal scales. Others still depend on the complexity of spatial forms and refer to the fractality of disasters. Finally, a last form of complexity is related to nonlinear dynamics. These various forms of complexity don't exclude each other, but could be

combined. Within the scope of this paper, we focus our attention on structural and dynamic complexities of catastrophes and on the possibility of modelling and simulating its double complexity with a formal and methodological framework: the General Systems Theory and System Dynamics modelling. We then briefly propose a model of urban catastrophe related to a flood. We then propose some ways of research allowing exceeding the limits related to the modelling.

## **STRUCTURAL AND DYNAMIC COMPLEXITIES OF RISK AND CATASTROPHE SYSTEMS**

Sciences of complexity propose a holistic approach to understand these phenomena. The holistic analysis seeks to understand systems mechanics by focusing not only on the entities which compose a system, but on the relations existing between these entities (Ménard et al. 2005). Initially we will try to identify structural complexity of risk and catastrophe systems by undertaking this holistic approach. Two levels of structural complexities could then be identified. The first level depends on the even definition of catastrophe. This is defined by risk specialists as a combination of hazard and vulnerability ( $R = A * V$ ). However we prefer to abandon this term of combination, which doesn't integrate interactions between constituents and define disaster as a complex set of hazard(s) and vulnerability(ies). These two entities form the core constituents of catastrophe systems and their global functioning. In the absence of one or the other of these constituents, there cannot be a disaster. Thus, catastrophes are emergent phenomena of hazard and vulnerability. The

emergence means that the global properties of the system cannot be deduced from the only knowledge of these entities (Zwirn 2005). If we neglect an essential aspect of a complex system, we cannot understand the system in its globality. This means that the risk can't be reduced neither to the one or other one of its parts nor to the sum of its parts. This is an important finding. For a long time, the terms of risk and hazard were used as synonyms, especially in the field of natural risks, such as floods and earthquakes. As a consequence this simplified version of the concept of catastrophe had to favour reductionist approaches in this domain. Scientific research widely privileged the study of risks only from the angle of the hazard. Of course, scientific progress in this domain was particularly important. In fact, by neglecting the vulnerability entity and therefore omitting a part of the system, important aspects of the structure and the global behaviour of disasters were missed out. Initially, in the Anglo-Saxon literature, the term "hazard" is used to describe as well hazard as risk, two terms which are in fact very different. The sciences of the complexity thus developed the concept of risk.

The other type of complexity is relative to the increase of the levels of complexity when we go from some sector-related complex risk (hazard, vulnerability) to transversal complex risk (hazard, vulnerability and "domino effects") (Dauphiné 2003). This increase of the levels of complexity results not only from the even higher number of constituents but also and especially from the multiplicity of the interactions which unite the various entities of a catastrophe. So, the transversal complex risk integrates the varied nature of "domino effects": natural and technical or technological, natural and social or still, to take a last example, natural, technical and social. These "domino effects", particularly in urban areas, are creative of clearing of multiple thresholds of gravity in varied domains and for the same "hyperdisaster" (Guihou et al. 2006). This structural complexity is rarely taken into account by the managers of disasters, which often study only one category of disaster: the risk of floods, earthquakes, forest fires, tsunamis, nuclear accidents etc. are identified in the various documents of prevention and management of the major risks (Municipal Document of Information on Major Risks). But these various documents don't integrate the transverse complexity of catastrophes which take place in urban areas. Some exceptions exist in this domain, notably in Japan, where the authorities of Tokyo are afraid of a chain

of natural and technological disasters following an earthquake (Hadfield 1992).

The Cartesian approach, which is limited mostly to the analysis of one type of risk, does not support the understanding of all the mechanics of a disaster. This scientific method tends at present to be replaced by holistic approaches. For the better understanding of a catastrophic event, the study of relations and interactions is better than the study of the system constituents.


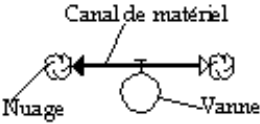


The second form of complexity depends on the dynamic and unpredictable complexities of the disaster systems. The General System Theory of Ludwig von Bertalanffy and the systemic modelling offer a formal frame to build models of disasters which are centred on the complexity of the relations man / nature and on nonlinear dynamics. Within the framework of the General System Theory, the System Dynamic of J.W. Forrester (Forrester 1984; Aracil 1984) is interested in the changes which occur inside the studied systems. This method of modelling and simulation of complex systems appeared in the early 1960s when J.W. Forrester was a professor at "Sloan School of management" of MIT (Massachusetts Institute of Technology). They were developed in France from 1980 on, with the translation into French of his book "Principles of Systems". The models allowing apprehending the dynamics of a system base themselves on the concepts of interaction, feedback loops and complexity. The dynamic and unpredictable complexities of catastrophe systems result from feedback loops (a circle of cause-and-effect) which connect the different variables of the system, the interactions between these feedback loops and the delays between variables and nonlinear phenomena (Donnadieu and Karsky 2002). Two kinds of feedback relationships govern the dynamic systems of a catastrophe. Some push the system towards instability and disorder. These are positive feedback loops. Others make the system return to its initial state. These are negative feedback loops. These two kinds of feedback relationships operate in complex systems. The presence of these circuits of feedback loops, which can occur either simultaneously or successively, does not allow, without modelling and simulation, to predict the temporal dynamics of a system. This dynamic complexity will be increased by the presence of a temporal gap and non-linearity between variables (no proportionality between cause and effect). In the event of a disaster, the planning and the intervention of disaster managers are forces which, normally but not systematically, bring the system to stability and order. On

the other hand, negative forces can push the system to disorder and to instability.

The System Dynamics modelling was thus retained to build models of urban disasters. The construction of a model starts by the realization of a Forrester diagram. This diagram represents the various elements which compose the system in term of stocks and flows, and clarify the relations established between the various variables of the modelled system. It is what we call the “Dynamo language”. The relations between the variables of the system are mathematically formulated with for example statistical laws, logical rules (if then else). In this way quantitative and qualitative data can be integrated into the model. The basic elements of the model are the state variables, flows, converters and connectors. It is difficult to separate this approach of the computer tool allowing its application.

## SYSTEM DYNAMICS MODELLING OF CATASTROPHE WITH THE STELLA RESEARCH PROGRAM

At the moment, Stella Research ® is one of the most wide-spread software to model and simulate the complex systems according to the principles of a formalization of Forrester. This software includes two modules: a graphic module which supports building the structure of the model. A mathematical module presents the results in the form of curves which is a set of differential equations defined by the graphic module. These differential equations are discretized in difference equations in the software Stella Research ®. The main symbols of the graphic module of the software Stella Research ® are represented in the table below:

	<p>Stocks or reservoirs, the graphic formalism of it is a rectangle, are state variables. Their quantity varies through time according to the inflows and outflows. The value of these stocks informs about the state of the system all the time t. Stocks are used to represent so many material accumulations (the water, the individuals) as immaterial (the knowledge)</p>
	<p>Flows feed the reservoir and thus modify the state. They determine the variations at the various levels of the system. In the absence of flows, no change in the magnitude of stocks is possible. So, stocks and flows are inseparable.</p>
	<p>The auxiliary variables or converters, represented by a circle, appear in connectors. They can be a constant, or a function according to time t or of a some variable a. These auxiliary variables are very useful to integrate qualitative information and delays into the models. They also allow to couple flows of different nature, for example flows of motorcars and motorist flows.</p>
	<p>The connectors allow to link together the variables of the system and to simulate feedback loops. Connectors link stocks to converters, stocks to flow, converters to flow and converters to other converters.</p>

**Table 1: Presentation of the main symbols of the graphic module of the software Stella Research ®**

This software was used to create a model of urban disaster of natural origin, a flood. This model (figure 1) has already been the object of publications (Provitolo 2003, 2005). We invite the reader interested in greater details of the structure and the results of the simulation to refer to these publications. The originality of this model is to associate various entities of disaster and its “domino effects”, namely the flood hazard (in this case, we have only considered riverine floods), the vulnerability of the population during the flood, the problems of urban traffic and of evacuation of the motorists as well as a module of

panic. The system of disaster is in this case constituted by four modules in interaction. The module of hazard establishes a link between the modules of the vulnerability of the population subject to a flood. Indeed, the exposed population is a function of the area (km<sup>2</sup>) flooded by river flood (module hazard). This hazard, physical phenomenon at the origin of the damages, is also going to have impacts on the urban traffic. It can provoke movements of panic amongst the motorists taken by the streams. These movements of panic, which can lead to acts of abandonment of vehicles, go then retroact on the module

of the vulnerability by delaying the arrival of emergency services. This global model of disaster thus associates aspects generally treated independently of each other. Every module is constituted, under graphic shape, by state variables, flows and connectors. These graphic models are then transformed into computer models which allow running simulations. The results of simulations are curves which show the temporal dynamics of the catastrophe.

According to the values of the various parameters of the model (policies of prevention, rapidity of intervention of the emergency services, rate of contact and contagion of the panic), the forms of the dynamics of the catastrophe system modify. So, the system knows different evolutions.

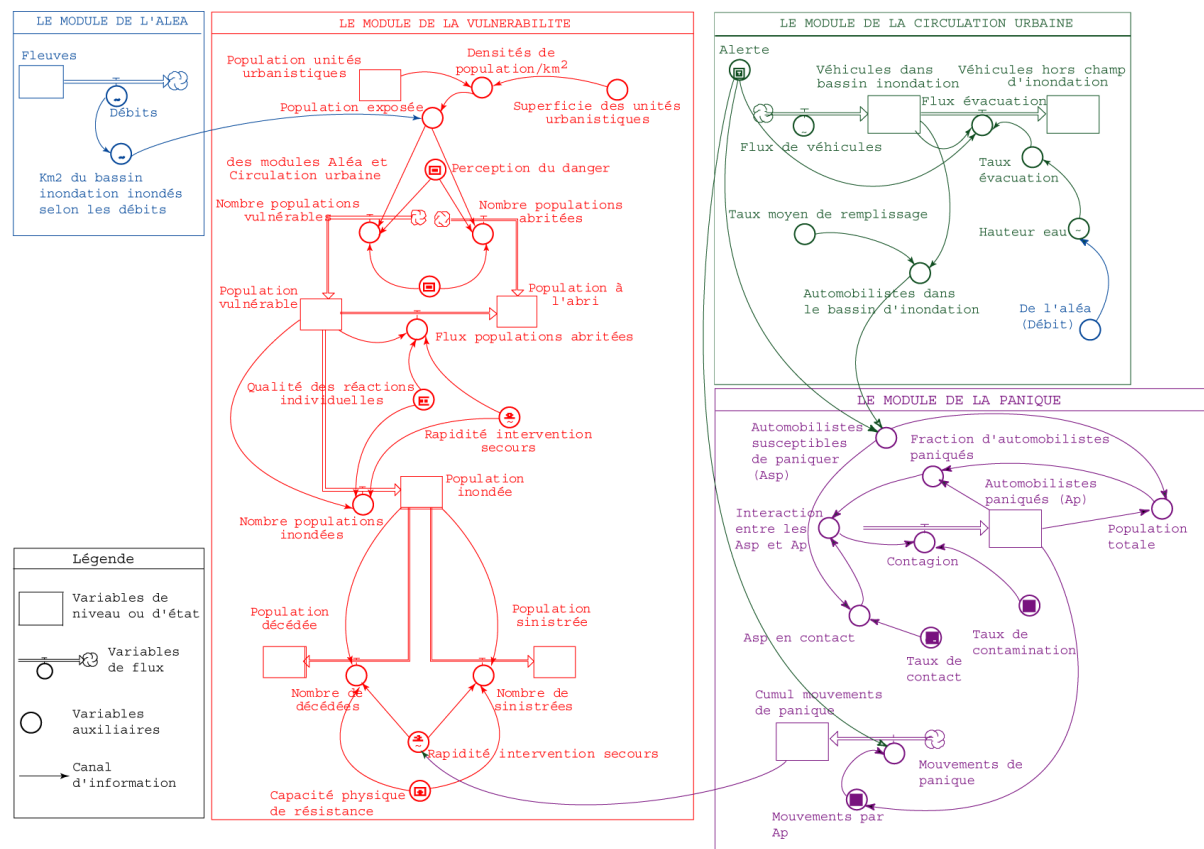


Figure 1: A catastrophe system

## CONCLUSION

This System Dynamics modelling offers a formal and methodological frame to apprehend the complex structures of type of disasters (natural, technological, social risk) and different kinds (flood, earthquake, terrorism) as well as their temporal dynamics. This modelling allows analysing the global nature of catastrophes. However this approach has limitations, notably with respect to the consideration of the space.

It does not adopt the same behaviour. Also the simulations lead to results which are counter-intuitive, unpredictable: the decrease of the rate of contact and contagion which build the relation between panic and not panic persons does not decrease the stocks of "contaminated" population, here, that of panic motorists. With nonlinear dynamics, the system can thus adopt unpredictable behaviour. These results of the simulation, by giving various possible evolutions of the system, are a tool of understanding. They also impose a rule of conduct. The models have to be the object of simulations based not only on average but also on extreme values of parameters. It is the most effective way of observing the variety of trajectories.

The space is indeed indirectly integrated into the models, for example by means of densities or of surfaces. To exceed this limitation, the "systemicien" can use other tools of modelling. The scientists have two solutions to integrate space in all its heterogeneousness and realize models which take into account temporal and spatial dynamics of a catastrophic event. The first solution is to link a Geographic Information System (G.I.S.) with a model of system dynamics to integrate the spatial

constituent. Currently, the G.I.S. allows combinatorial analyses and structures, but on the other hand is less capable of modelling and simulating dynamics and complex dynamics. It is very likely that these limitations will be overcome within the next years. The second approach is to combine System Dynamics modelling with cellular automata. This research is in progress at the University of Maryland. The philosophy of this spatio-temporal modelling is to integrate the spatial systems, the simulation and the complexity into the problem of risk. So we could have the possibility of working on a spatial grid of square unit cells (raster) representing an urban area. In each of these cells a model of System Dynamics

of catastrophe (model of type stock-flow) would be connected. The same structure of model would run in each cell. In this way we would obtain interactions between the cell and the systemic model, namely between the urban shape and the variables of the catastrophe system (hazard, vulnerability and “domino effects”). This architecture of models in interaction would allow understanding not only the spatial dynamics but also the temporal dynamics of the catastrophe. These research efforts are certainly worth to be further developed. Indeed, the knowledge obtained by these simulations would certainly allow taking up new forms of management of disasters.

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